ERDC/CRREL TN-13-1

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

ERDC
INNOVATIVE SOLUTIONS for a safer, better world

Engineering for Polar Operations, Logistics and Research (EPOLAR)

Thermal Conductivity and Durability Testing of Inflatable Building Materials

Jason C. Weale and Margaret A. Knuth

September 2013

The US Army Engineer Research and Development Center (ERDC) solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at www.erdc.usace.army.mil.

To search for other technical reports published by ERDC, visit the ERDC online library at http://acwc.sdp.sirsi.net/client/default.

ERDC/CRREL TN-13-1
September 2013

Thermal Conductivity and Durability Testing of Inflatable Building Materials

Jason C. Weale and Margaret A. Knuth

Cold Regions Research and Engineering Laboratory (CRREL)
US Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755

Final report

Approved for public release; distribution is unlimited.

Prepared for National Science Foundation, Office of Polar Programs,
Arctic Sciences Research Support and Logistics Program

Under Engineering for Polar Operations, Logistics and Research (EPOLAR)

Abstract

The National Science Foundation's Arctic Sciences Research Support and Logistics Program (NSF ARC-RSL) is interested in employing new and emerging building technologies to expand the number of shelter options available for supporting operations in Polar Regions. Rapidly deployable, lightweight, portable, cost effective, inflatable, and insulated fabric structures offer potential solutions to meet these needs. Thermal conductivity and durability tests were conducted on commercial, off-the-shelf (COTS) outer shell and inner insulation fabrics. The fabrics consisted of single and double-sided polyurethane coated nylon and drop thread shell samples and both polyester and Thinsulate insulation layers. These samples underwent 10 cycles of bending and folding following 6 hours of cold soaking at −40°C to assess durability. Thermal conductivity tests were completed in a LaserComp test instrument and reported as R-values to compare thermal resistivity (insulating) properties. Finally, we compared various built-up wall sections (shell materials with single and multiple layers of insulating materials) and normalized the results to cost per unit per R ($\$/yd^2/R$). The normalized results identified an optimum shell and insulation combination to pursue for fabrication and testing of prototype, full scale inflatable structures in Polar Regions.

Table of Contents

List of Figures and Tables

Figures

Tables

Preface

This study was conducted for the National Science Foundation under Engineering for Polar Operations, Logistics and Research (EPOLAR) EP-ARC-11-17, “Field Evaluation of Inflatable Airbeam Buildings.” At the time of publication, Jennifer Mercer was the program manager for EPOLAR.

The work was performed by Jason C. Weale and Margaret A. Knuth (Force Projection and Sustainment Branch, Dr. Edel Cortez, Chief), US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Justin Berman was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

COL Jeffrey R. Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
R-value (US)[1]	0.1761101838	R-value (RSI)
square yards	0.8361274	square meters
yards	0.9144	meters

[1] R value = 1/thermal conductance per inch thickness of the material. Other methods for converting between SI and US units of R-value are 1 $h \cdot ft^2 \cdot °F/Btu = 0.176110\ K \cdot m^2/W$, 1 $K \cdot m^2/W = 5.678263\ h \cdot ft^2 \cdot °F/Btu$, or R-value (US) = RSI × 5.678263337. All R-values in this report are presented in US units.

1 Background

The National Science Foundation Arctic Sciences Research Support and Logistics Program (NSF ARC-RSL) is interested in using new technologies to increase the variety of building structures available for use in the field. Inflatable structures offer the potential to provide a rapidly deployable, logistically efficient (lower weight, ease of setup, smaller cargo space required, etc.), cost-effective shelter for use in cold climates. Including insulating layers in addition to the air space could also make the structures more energy-efficient than traditional tent structures or conventionally-constructed buildings. Recent communications with and site visits to third-party vendors (e.g., ILC Dover) and to the US Army Natick Soldier Research Development and Engineering Center led to the idea of conducting thermal conductivity and durability tests on an insulated, inflatable building concept. We note that standard low temperature tests do not exist, at the time of publication, that accurately account for the proposed field application of these technologies. The low temperature material property (rating) typically reported in material specifications is the temperature at which the material becomes brittle and shatters during impact. It does not predict the performance of these materials in dynamic environments at relatively “warmer” temperatures when compared to the brittleness temperature. This report presents the methods and results obtained from the durability and thermal resistivity tests.

2 Materials and Test Procedures

At NSF's request to third-party vendors and Natick, CRREL received samples of four potential materials that could be used as inflatable skins (Table 1) and four potential insulating materials (Table 2). A required R-value was not established prior to the tests, as the objective of this effort was to learn the relative insulating values of potential solutions and to develop cost comparisons normalized by respective R-values.

Table 1. Potential building skin materials.

Building skin material	Thickness (in./layer) as tested	Unit cost (yd^2)
Tan Polyurethane Double-Sided Coated Nylon	0.027	$20.70
Blue Polyurethane Single-Sided Coated Nylon	0.0095	$5.86
White Polyurethane Single-Sided Coated Nylon	0.0095	$5.86
Blue Drop Thread Fabric	0.1260	$46.00

Table 2. Potential insulating materials:

Insulating material	Thickness (in./layer) as tested	Unit Cost (yd^2)
Thinsulate G200 with 3M Backing	0.25	$3.14
Thinsulate G200 without Backing	0.375	$3.14
Polyester/Cotton Blend (20%/80%)	0.066	$3.40
100% Polyester	0.375	$5.00

We tested each material in our LaserComp thermal conductivity measurement instrument to determine its thermal conductivity and calculate the corresponding R-value. The test instrument consisted of horizontal flat plates set to prescribed temperatures with a 12 × 12 in. sample of test material sandwiched in the middle. Given that the insulating properties of materials can change with temperature, the top plate was set at 4°F and the bottom plate was set at 60°F to best reflect the anticipated exterior and interior field conditions of a rapid deployed fabric tent structure in Greenland in the summer (the likely test location for a prototype structure built from one of these materials).

Once the temperature field within the test material stabilized, we could determine by the instrument's calibrated transducers the temperature gradient between the hot and cold plates. The software algorithm used the results and the one-dimensional Fourier law to calculate the material's thermal conductivity and report its resistance to heat flow. Figure 1 shows an image of the LaserComp test instrument. We also constructed and tested "sandwich panels" consisting of one layer of building skin and single or multiple layers of insulation to obtain the thermal conductivity and calculate the R-values of various wall sections.

Figure 1. LaserComp thermal conductivity test instrument.

We conducted the durability tests in CRREL's −40°C cold box. Samples of each of the eight materials (6 × 6 in.) were "cold soaked" lying flat for approximately 6 hours at −40°C. We individually flexed and creased the samples, by hand, for 10 cycles. The folds were alternated from 90 degrees forward (first cycle) to 90 degrees back (second cycle) to determine qualitatively if any cracking would occur during bending from a flat shape to a doubled-over shape. We did not account for potential warming of each sample from human hands but note that the folds were conducted in rapid sequence such that we estimated minimal warming affect. The project included a second set of durability tests. The samples were initially folded 90 degrees (in half) and placed back in the cold box with a weight on top, to keep them folded; and they were cold soaked to −40°C again overnight. We unfolded each sample slowly to determine whether it cracked on the initial bend, and each was subsequently creased over 10-cycles (as before)

to see if repeated bending would cause any cracking. Figure 2 shows the cold box with a folded sample.

Figure 2. Sample undergoing cycling in −40°C Cold Box.

3 Results

3.1 Thermal conductivity

Figure 3 and Table 3 present the results of the thermal conductivity tests on 12 different sandwich panels. All samples displayed a virtually linear increase in R-value with thickness. Table 4 presents the thickness of each sandwich panel sample as tested. We expected the linear trend when increasing the wall section thickness with the same material. Thus, the results appeared accurate and were also repeatable. The blue or white polyurethane single-sided coated nylon with three layers of unbacked Thinsulate G200 had the highest measured R-value (5.29). The drop-thread material with one layer of 3M-backed Thinsulate G200 gave the lowest R-value (1.05).

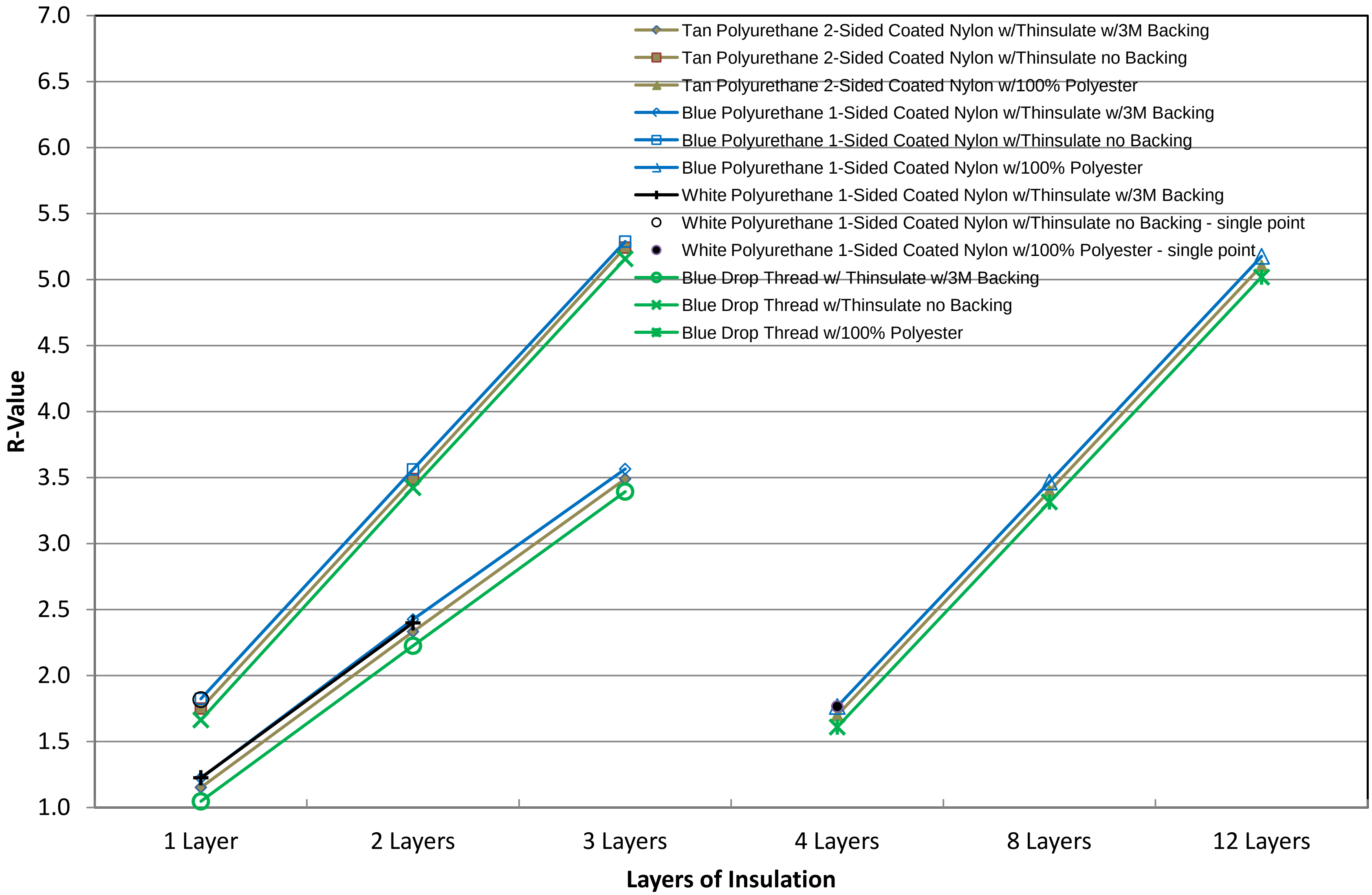

Figure 3. R-value (US) test results for insulated, inflatable building materials.

Table 3. R-value (US) test results for insulated, inflatable building materials.

Number of insulating layers	Tan polyurethane double-sided coated nylon w/Thinsulate w/3M backing	Tan polyurethane double-sided coated nylon w/Thinsulate without backing	Tan polyurethane double-sided coated nylon w/100% polyester	Blue polyurethane single-sided coated nylon w/Thinsulate w/3M backing	Blue polyurethane single-sided coated nylon w/Thinsulate without backing	Blue polyurethane single-sided coated nylon w/100% polyester
1	1.153	1.7505		1.224	***1.824***	
2	2.333	3.489		2.4255	***3.562***	
3	3.49	5.242		3.565	***5.2878***	
4			1.7			***1.766***
8			3.4			***3.466***
12			5.104			***5.176***

Number of insulating layers	White polyurethane single-sided coated nylon w/Thinsulate w/3M backing	White polyurethane single-sided coated nylon w/Thinsulate without backing	White polyurethane single-sided coated nylon w/100% polyester	Blue drop thread w/Thinsulate w/3M backing	Blue drop thread w/Thinsulate without backing	Blue drop thread w/100% polyester
1	1.226	1.818		1.047	1.664	
2	2.399	**		2.226	3.423	
3	**	**		3.394	5.157	
4			1.766			1.61
8			**			3.315
12			**			5.0185

*Highlighted values in this table are averages of original tests and repeated tests. The Tests were accurate and repeatable.

**Tests not repeated because of similar results with both blue and white polyurethanes—they have essentially the same R-value.

Values in ***Bold Italics*** were the highest measured R-values for given number of layers.

Table 4. Thickness (in.) of each wall section, including shell material, as tested.

Number of insulating layers	Tan polyurethane double-sided coated nylon w/Thinsulate w/3M backing	Tan polyurethane double-sided coated nylon w/Thinsulate without backing	Tan polyurethane double-sided coated nylon w/100% polyester	Blue polyurethane single-sided coated nylon w/Thinsulate w/3M backing	Blue polyurethane single-sided coated nylon w/Thinsulate without backing	Blue polyurethane single-sided coated nylon w/100% polyester
1	0.250	0.375		0.250	0.375	
2	0.500	0.750		0.500	0.750	
3	0.750	1.125		0.750	1.125	
4			0.375			0.375
8			0.750			0.750
12			1.125			1.125

Number of insulating layers	White polyurethane single-sided coated nylon w/Thinsulate w/3m backing	White polyurethane single-sided coated nylon w/Thinsulate without backing—single point only	White polyurethane single-sided coated nylon w/100% polyester—single point only	Blue drop thread w/Thinsulate w/3m backing	Blue drop thread w/Thinsulate without backing	Blue drop thread w/100% polyester
1	0.250	0.375		0.250	0.375	
2	0.500	**		0.500	0.750	
3	**	**		0.750	1.125	
4			0.375			0.375
8			**			0.750
12			**			1.125

**Tests not repeated because of similar results with both blue and white polyurethanes—they are the same thickness.

Along with the significant variability in R-values (4.13) over the range of these configurations, there were also significant cost differences. Table 5 presents the estimated cost for a square yard of each sandwich panel configuration. The sample that yielded the highest R-value (blue or white polyurethane single-sided coated nylon with three layers of unbacked Thinsulate G200) cost approximately $15.28/yd^2. In general, the polyurethane single-sided coated nylon panels were the cheapest at approximately $9 to $66/yd^2; the polyurethane double-sided coated nylon panels were mid-range at approximately $24 to $81/yd^2; and the drop thread panels were by far the most expensive at $49 to $106/yd^2. The range of costs associated with each shell material reflects the number of layers of insulating material contained in each sample wall section. A quick look at the cost of

insulation indicates the Thinsulate G200 (same cost and R-value backed or unbacked) is the best value at approximately $3.14/yd^2$.

Table 5. Estimated cost per unit (yd^2) for insulated, inflatable building materials.

Number of insulating layers	Tan polyurethane double-sided coated nylon w/Thinsulate w/3M backing	Tan polyurethane double-sided coated nylon w/Thinsulate without backing	Tan polyurethane double-sided coated nylon w/100% polyester	Blue polyurethane single-sided coated nylon w/Thinsulate w/3M backing	Blue polyurethane single-sided coated nylon w/Thinsulate without backing	Blue polyurethane single-sided coated nylon w/100% polyester
1	$23.84	$23.84		$9.00	$9.00	
2	$26.98	$26.98		$12.14	$12.14	
3	$30.12	$30.12		$15.28	$15.28	
4			$40.70			$25.86
8			$60.70			$45.86
12			$80.70			$65.86

Number of insulating layers	White polyurethane single-sided coated nylon w/Thinsulate w/3M backing	White polyurethane single-sided coated nylon w/Thinsulate without backing	White polyurethane single-sided coated nylon w/100% polyester	Blue drop thread w/ Thinsulate w/3M backing	Blue drop thread w/Thinsulate without backing	Blue drop thread w/100% polyester
1	$9.00	$9.00		$49.14	$49.14	
2	$12.14	**		$52.28	$52.28	
3	**	**		$55.42	$55.42	
4			$25.86			$66.00
8			**			$86.00
12			**			$106.00

**Tests not repeated because of similar results with both blue and white polyurethanes—they have the same cost as blue poly.

3.2 Durability

We conducted the first set of durability tests after cold soaking the samples for 6 hours. All samples, except the drop thread fabric, performed adequately after being cold soaked at −40°C and flexed for 10 cycles from lying flat. The polyurethane samples demonstrated very minor increases in stiffness, and all of the insulation samples behaved as they did at normal room temperatures. The drop thread material was very stiff, produced audible cracking, and ultimately delaminated during this test (Fig. 4).

Figure 4. Delamination of drop thread fabric after bending.

We obtained similar results when the materials were cold soaked overnight in the flexed orientation, unfolded, and cycled 10 additional times. The drop thread sample displayed “bubbling” from further delamination (Fig. 5), and the internal fibers appeared to either separate or rip as well (Fig. 6). In addition, the polyester/cotton insulation sample collected moisture. It is unclear if that was a result of the cotton or if it was because of the high humidity it experienced during the test period. Table 6 discusses the durability.

Figure 5. “Bubbling” of drop thread fabric caused by delamination.

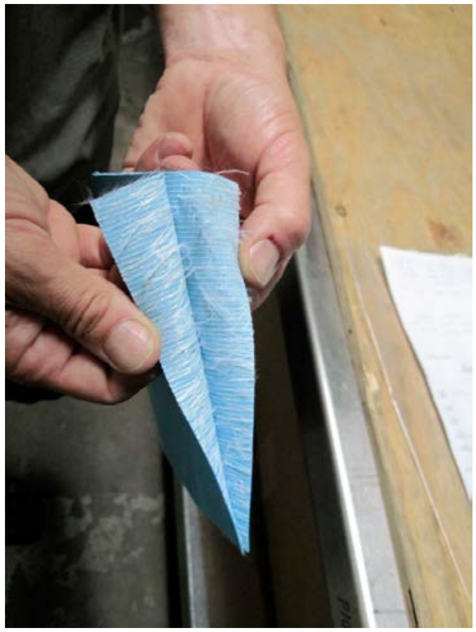

Figure 6. Ripping and separation of drop thread fibers.

Table 6. Cold/durability testing at −40°C

Test Case #1: Cold soak flat and cycle with 10 bends		
Sample #	Sample description	Comments on bend cycling
1D	Tan polyurethane double-sided coated nylon	No cracking, very little increase in stiffness
2D	Blue polyurethane single-sided coated nylon	No cracking, very little increase in stiffness
3D	White polyurethane single-sided coated nylon	No cracking, very little increase in stiffness
4D	Thinsulate with 3m backing	No cracking, no increase in stiffness
5D	Thinsulate without backing	No cracking, no increase in stiffness
6D	Blue drop thread	Audible cracking, very stiff, delaminated
6aD	20%polyester with 80%cotton	No cracking, no increase in stiffness
7D	100% polyester	No cracking, no increase in stiffness

Test Case #2: Cold soak doubled over and cycle with 10 bends		
Sample #	Sample description	Comments on bend cycling
1D	Tan polyurethane double-sided coated nylon	No cracking, was stiff after cold soak
2D	Blue polyurethane single-sided coated nylon	No effect
3D	White polyurethane single-sided coated nylon	No effect
4D	Thinsulate with 3m backing	No cracking, stuck together (perhaps due to high humidity)
5D	Thinsulate without backing	No cracking, stuck together (perhaps due to high humidity)
6D	Blue drop thread	Loud cracking, delamination, ripples, fibers appear to be separating/ripping
6aD	20%polyester with 80%cotton	No change, collected some moisture (perhaps due to high humidity)
7D	100% polyester	No change

4 Conclusions and Recommendations

CRREL conducted a series of thermal conductivity and durability tests on potential materials for constructing inflatable building wall-sections. The results of the R-value tests indicated that the blue or white polyurethane single-sided coated nylon building skin with three layers of unbacked Thinsulate G200 insulation yielded the highest R-value, 5.29. Those materials also remained flexible at −40°C and survived repeated bending and folding with only very minor stiffening and no indication of cracking or material damage. Though at roughly $15/yd² it wasn't the overall cheapest wall section tested, when we normalized the costs by R-value (Table 7) it was the most thermally efficient combination (approximately $3/yd²/R). Two factors of particular importance during development of this concept are (1) to be sure that both the wall shell material and the insulating material remain flexible at cold temperatures and (2) to ensure that the insulating material remain hydrophobic at all times—that is more important than achieving a slightly higher R-value when comparing competing materials. This factor ruled-out further consideration of cotton and other uncoated, moisture-susceptible materials.

Based on measured R-values and qualitative durability test results combined with the unit cost/R, CRREL recommends pursuing the polyurethane single-sided coated nylon (or similar product) with a single layer of Thinsulate (or similar insulation) as a prototype wall section for inflatable structures in Polar Regions. To obtain a more complete understanding of anticipated field performance of these materials, we also recommend prototype wall sections undergo accelerated UV exposure tests, abrasion tests at cold temperature, and cyclic tensile tests. These tests can help provide quantitative durability performance results.

Table 7. Estimated cost per unit, normalized by R-value ($\$/yd^2/R$)

Number of insulating layers	Tan polyurethane double-sided coated nylon w/Thinsulate w/3m backing	Tan polyurethane double-sided coated nylon w/Thinsulate without backing	Tan polyurethane double-sided coated nylon w/100% polyester	Blue polyurethane single-sided coated nylon w/Thinsulate w/3m backing	Blue polyurethane single-sided coated nylon w/Thinsulate without backing	Blue polyurethane single-sided coated nylon w/100% polyester
1	$20.68	$13.62		$7.35	$4.93	
2	$11.56	$7.73		$5.01	$3.41	
3	$8.63	$5.75		$4.29	$2.89	
4			$23.94			$14.64
8			$17.85			$13.23
12			$15.81			$12.72

Number of insulating layers	White polyurethane single-sided coated nylon w/Thinsulate w/3M backing	White polyurethane single-sided coated nylon w/Thinsulate without backing	White polyurethane single-sided coated nylon w/100% polyester	Blue drop thread w/ Thinsulate w/3m backing	Blue drop thread w/Thinsulate without backing	Blue drop thread w/100% polyester
1	$7.34	$4.95		$46.93	$29.53	
2	$5.06	**		$23.49	$15.27	
3	**	**		$16.33	$10.75	
4			$14.64			$40.99
8			**			$25.94
12			**			$21.12

**Tests not repeated because of similar results with both blue and white polyurethanes—they have the same unit cost as blue poly.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
September 2013

2. REPORT TYPE
Technical Note/Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Thermal Conductivity and Durability Testing of Inflatable Building Materials

5a. CONTRACT NUMBER
EP-ARC-11-17

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jason C. Weale and Margaret A. Knuth

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Cold Regions Research and Engineering Laboratory (CRREL)
US Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CRREL TN-13-1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Science Foundation, Office of Polar Programs,
Arctic Sciences Research Support and Logistics Program

10. SPONSOR/MONITOR'S ACRONYM(S)
NSF/EPOLAR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Engineering for Polar Operations, Logistics and Research (EPOLAR)

14. ABSTRACT

The National Science Foundation's Arctic Sciences Research Support and Logistics Program (NSF ARC-RSL) is interested in employing new and emerging building technologies to expand the number of shelter options available for supporting operations in Polar Regions. Rapidly deployable, lightweight, portable, cost effective, inflatable, and insulated fabric structures offer potential solutions to meet these needs. Thermal conductivity and durability tests were conducted on commercial, off-the-shelf (COTS) outer shell and inner insulation fabrics. The fabrics consisted of single and double-sided polyurethane coated nylon and drop thread shell samples and both polyester and Thinsulate insulation layers. These samples underwent 10 cycles of bending and folding following 6 hours of cold soaking at −40°C to assess durability. Thermal conductivity tests were completed in a LaserComp test instrument and reported as R-values to compare thermal resistivity (insulating) properties. Finally, we compared various built-up wall sections (shell materials with single and multiple layers of insulating materials) and normalized the results to cost per unit per R ($/yd2/R). The normalized results identified an optimum shell and insulation combination to pursue for fabrication and testing of prototype, full scale inflatable structures in Polar Regions.

15. SUBJECT TERMS

	Inflatable building	Insulated inflatable structures
Durability tests	Insulated inflatable building	R-value tests
Expedient cold climate shelter	Insulated inflatable building material tests	Thermal conductivity tests

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	U	22	